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Single-Leg Hop Performance After Anterior Cruciate Ligament Reconstruction: Ready for Landing but Cleared for Take-Off?

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Context: Although the landing phases of the single-leg hop for distance (SLHD) are commonly assessed, limited work reflects how the take-off phase influences hop performance in patients with anterior cruciate ligament reconstruction (ACLR).

Objective: To compare trunk and lower extremity biomechanics between individuals with ACLR and matched uninjured controls during take-off of the SLHD.

Design: Cross-sectional study design.

Setting: Laboratory setting.

Patients or Other Participants: Sixteen individuals with ACLR and 18 uninjured controls.

Main Outcome Measure(s): Normalized quadriceps isokinetic torque, hop distance, and respective limb symmetry indices were collected for each participant. Sagittal and frontal kinematics and kinetics of the trunk, hip, knee, and ankle as well as vertical and horizontal ground reaction forces were recorded for loading and propulsion of the take-off phase of the SLHD.

Results: Those with ACLR had weaker quadriceps peak torque in the involved limb ($P = .001$) and greater strength asymmetry ($P < .001$) than control individuals. Normalized hop distance was not statistically different between limbs or between groups ($P > .05$), and hop distance symmetry was not different between groups ($P > .05$). During loading, the involved limb demonstrated lesser knee flexion angles ($P = .030$) and knee power ($P = .007$) than the uninvolved limb and lesser knee extension moments than the uninvolved limb ($P = .001$) and controls ($P = .005$). During propulsion, the involved limb demonstrated lesser knee extension moment ($P = .027$), knee power ($P = .010$), knee ($P = .032$) and ankle work ($P = .032$), and anterior-posterior ground reaction forces ($P = .047$) and greater knee ($P = .016$) abduction excursions than the uninvolved limb.

Conclusions: Between-limb differences in SLHD take-off suggest a knee underloading strategy in the involved limb. These results provide further evidence that distance covered during SLHD assessment can overestimate function and fail to identify compensatory biomechanical strategies.

Key Words: return-to-sport criteria, knee joint loading, biomechanics

Key Points

- Single-leg hop distance was similar between limbs and groups despite quadriceps strength asymmetry and biomechanical differences.
- Individuals with anterior cruciate ligament reconstruction underload the knee during single-leg hop take-off and preserve hop distance using a hip-dominant propulsion strategy.
- Quadriceps weakness is associated with reduced sagittal plane knee joint loading and sagittal plane hip, knee, and ankle excursions in the involved anterior cruciate ligament reconstruction limb.

Return-to-sport decision-making following anterior cruciate ligament reconstruction (ACLR) incorporates objective criteria and patient-reported function.[1,2] The single-leg hop for distance (SLHD) is the most used clinical surrogate of functional performance.[3] Hop tests simulate the patient's ability to produce muscle power and maintain neuromuscular control during landing.[4] A limb symmetry index (LSI) is used to quantify hop performance as an interlimb ratio, but this metric tends to overestimate function of the injured limb.[5] Although individuals with ACLR commonly achieve ≥90% LSI, they tend to have bilateral impairment in hop distance relative to preoperative estimates.[5] Additionally, large deficits in quadriceps strength symmetry between limbs are still present and have raised questions as to whether compensation strategies exist.[6,7] For example, greater quadriceps strength asymmetries have been associated with asymmetries of knee flexion angles and moments during the SLHD.[8]

Traditional hop testing approaches emphasize the quantification of hop distance and interlimb symmetry, which underemphasize how patients initiate and produce their movement. Very few studies have investigated how the take-off (onset of movement to when the foot leaves the ground) phase of the SLHD is influencing hop performance.[9–11] Collectively, these studies have reported lesser knee flexion of the involved limb during the propulsion phase of take-off, defined as the time from peak knee flexion to leaving the ground.[9–11] This may indicate that individuals with ACLR avoid greater knee flexion angles as a compensatory strategy for a reduced ability to load the knee due to persistent quadriceps weakness.[11] However, these investigations were limited to sagittal plane analysis, between-limb comparisons only, and emphasize the propulsion phase (ie, where forces are generated) without consideration of how these patients are loading before the propulsion phase. Additionally, the timing in which peak joint angles and loading occur during the take-off phases is unclear. A more comprehensive description of take-off kinematics and kinetics would provide further information as to how individuals with ACLR are generating movements and loading the lower extremities to achieve similar hop distances compared with the contralateral limb and uninjured controls. Biomechanical analysis of the take-off in individuals with ACLR may reveal compensatory load redistribution to proximal or distal joints (eg, trunk, hip, and ankle), indicating knee underloading. Such analysis offers valuable insights into SLHD strategies and joint loading beyond the traditionally emphasized end product (landing and distance) of the hop. Using only hop distance for a passing criterion may misinform the clinician on the patient's physical readiness to progress to functional activity. Individuals with ACLR have presented with knee joint underloading of the injured knee during activities of daily living, running, and drop landings that does not resolve over the course of rehabilitation and has been associated with cartilage degeneration biomarkers only a few years after ACLR.[12–16] Therefore, analyzing take-off biomechanics of the SLHD can inform targeted interventions aimed at restoring normative knee loading patterns during take-off that may contribute to preserving knee joint health.

The present study aims to further our understanding of functional loading of the ACLR limb to better inform clinical decision-making when progressing through functional activities and return to sport. Therefore, the primary objective of this study was to compare trunk and lower extremity kinematics and kinetics between individuals with ACLR and matched uninjured controls during take-off of the SLHD. We hypothesized that the involved limb would exhibit a hip- and ankle-dominant strategy (eg, greater hip flexion and dorsiflexion) compared with the contralateral and matched uninjured control limbs, where we expect to see underloading of the knee joint. Our secondary objective was to determine the relationships between quadriceps strength symmetry and biomechanical outcomes during the take-off phases in individuals with ACLR. We hypothesized that lesser quadriceps strength symmetry would associate with movement patterns that would off-load the ACLR joint during the loading and propulsion phases of the SLHD (eg, greater strength asymmetry associates with greater trunk and hip flexion, ankle plantar flexion).

METHODS

We used a descriptive laboratory study design. The independent variables included group (ACLR and control) and limb. Control limbs were matched by limb dominance. For example, if an individual with ACLR injured their dominant limb, as determined by which leg would be used to kick a ball, we matched with the control's dominant limb (ACLR: involved, uninvolved; control: matched involved, matched uninvolved). The dependent variables included sagittal and frontal plane kinematic (trunk, hip, knee, and ankle angles) and kinetic (hip, knee, and ankle moments, powers, work, and ground reaction forces [GRF]) variables. Uninjured participants were matched based on age (±2 years) and sex.

Participants

Participants were recruited from the university's general population and orthopedic departments. Thirty-four individuals participated in this study, including 16 with a history of ACLR and 18 uninjured controls. Individuals with primary unilateral ACLR between the ages of 15 and 45 were eligible to participate. Controls were eligible if they were between the ages of 15 and 45, had no history of lower extremity surgery, and had no history of lower extremity injury within the past 12 months at the time of enrollment. Exclusion criteria for both groups consisted of (1) known pregnancy at the time of enrollment, (2) diagnosed malignancy, (3) known muscular abnormalities, (4) history of cardiopulmonary disorders, (5) history of neuropathy, (6) and current use of any medications that may have influenced study outcome measures. Participants completed all testing procedures during a single session in a controlled laboratory setting, and procedures were approved by the University of Toledo Biomedical Institutional Review Board. All participants provided written and verbal informed consent before data collection.

Procedures

Quadriceps Strength Testing. Each participant completed a standardized warm-up before the start of collection, which consisted of 5 minutes of treadmill walking at a self-selected pace. Participants were positioned in a multimodal isokinetic dynamometer (System 4 Pro, Biodex Medical Systems) with their hips and knees flexed to 85° and 90°, respectively. They were then secured to the seat using shoulder and waist straps. The lower leg of the test limb was secured with a strap. Participants were familiarized with the task before performing 5 maximal effort concentric-concentric knee extension and flexion contractions at 60°/s. Participants moved through their full active range of motion, kicking to full knee extension and pulling into maximal knee flexion. The investigators provided verbal encouragement to ensure that maximal effort was given by the participant. These procedures were performed bilaterally. The order in which each limb was tested first was counterbalanced between participants, and this same order was used for motion analysis. The average peak knee

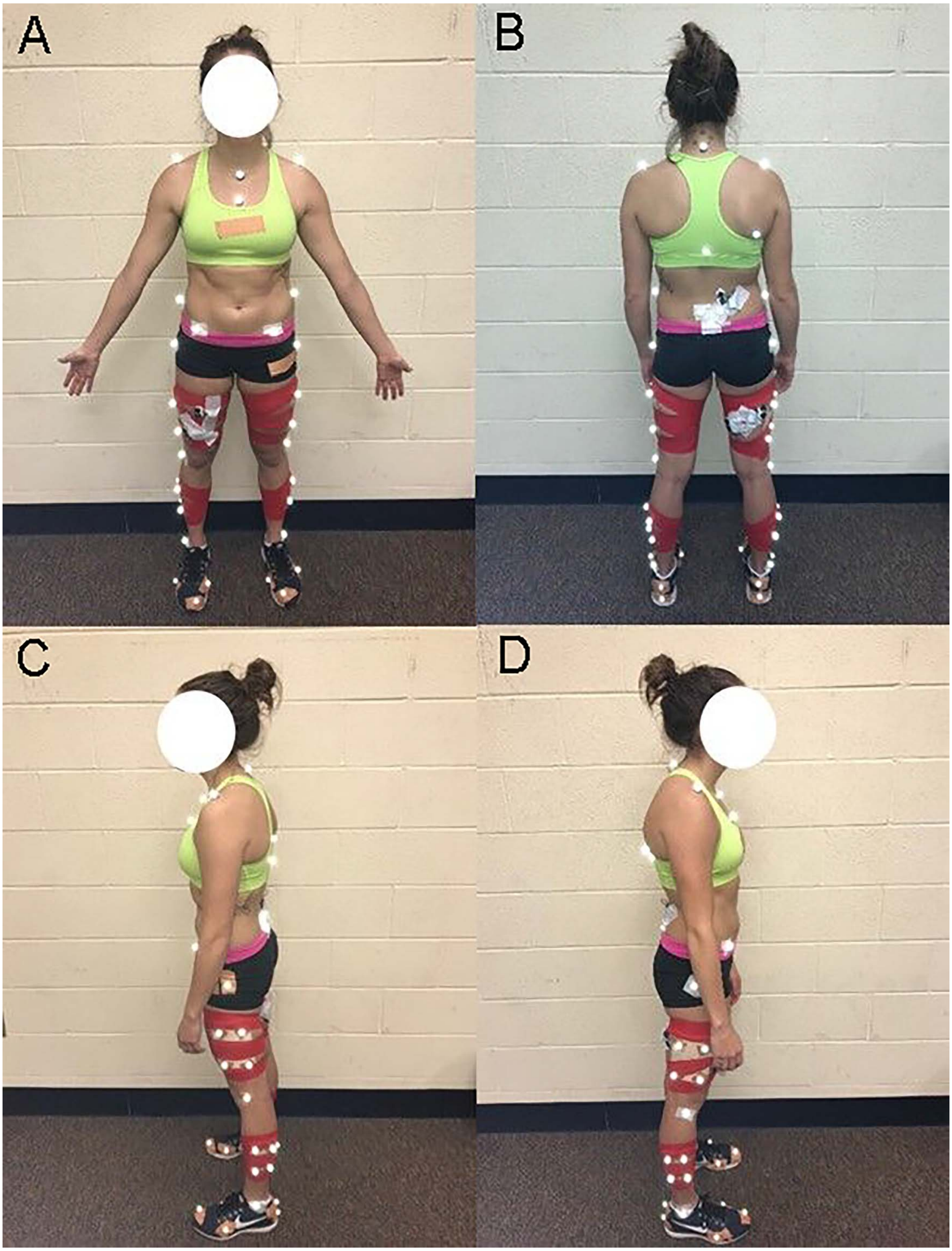

Figure. Marker placement for motion analysis data collection.

extension torque across all repetitions was normalized to body mass (Nm/kg). Limb symmetry was computed as the ratio of involved to uninvolved peak torque and expressed as a percentage.

Three-Dimensional Motion Analysis. Following strength testing, participants were outfitted with 50 retroreflective markers placed over anatomical boney landmarks of the trunk, pelvis, and bilateral lower extremities (Figure).[17] Rigid body clusters of 4 markers were secured bilaterally to the thigh and shank using Velcro straps and were used for tracking markers. Kinematic data were collected using 12-high-speed Raptor-E digital cameras (Motion Analysis Corporation), sampling at 120 Hz and synchronized with an imbedded force plate (OPT464508, Advanced Motion Technology, Inc) sampling at 1200 Hz using Cortex motion capture software (v. 7.2; Motion Analysis Corporation). Before completing the SLHD trials, a static calibration trial was captured, and bilateral anterior superior iliac spine landmarks were digitally marked using a spring-loaded digitizing pointer (C-Motion, Inc).[18]

For the SLHD, participants were positioned on the embedded force plate to start. The instructions for the counter-movement style SLHD were given based on previously described methods.[19] Participants were permitted a minimum of 3 practice trials to familiarize them with the task. During the recorded trials, participants completed as many trials as necessary until they performed 3 successful trials on each limb. A successful trial was defined as the participant controlling their landing position for 2 seconds without losing balance, shifting their foot, or touching the ground with their nonlanding foot.[20] Hop distance was recorded from toe (start) to heel (end) using a tape measure, and the average of 3 successful trials was normalized to the participants' body height for analysis. Limb symmetry was computed as the ratio of involved to uninvolved hop distance and was expressed as a percentage.

Using Visual3D, an 8-segment, subject-specific model was created (C-Motion, Inc). Joint centers for the hips and ankles were calculated from the static calibration trial, and knee joint centers were calculated using a functional joint center approach. Trunk, hip, knee, and ankle joint angles were defined based on previous literature and determined using an *X*-*Y*-*Z* Cardan sequence.[17] Ground reaction forces and joint moments and power were calculated using an inverse dynamics approach.

The take-off was broken down into loading and propulsion phases. The loading phase was defined as the instance when normalized vertical GRF (vGRF) decreased from the body weight (BW) force (vGRF $<$ 1 BW) to peak knee flexion of the stance limb.[21] The propulsion phase was defined as the instance of peak knee flexion of the stance limb to the time when participants left the force plate (when vGRF dropped below 10 N).[22] The data from each phase were time normalized to 100%. Peak sagittal and frontal joint angles and moments, anterior-posterior and vGRFs, and sagittal plane powers and work were identified across each trial and were averaged across the 3 trials. Sagittal and frontal plane joint excursions for the trunk, hip, knee, and ankle were assessed during the propulsion phase only. Excursions were expressed as the absolute change in degrees from the joint angle at the time of peak knee flexion to the peak joint excursion within the propulsion phase. All joint moments were expressed as internal moments and were normalized to the product of body mass and height (Nm/kg $\times$ m). Joint work was calculated using the net positive and negative joint power over a range of time for the hip, knee, and ankle. Work absorption was calculated from the onset of the SLHD to the instance positive joint power crossed zero in the positive direction. Work generation was calculated from the instance of positive power generation to toe-off of the propulsion phase. Power (W/kg) and work (J/kg) were normalized by body mass, and GRFs (BW) were normalized to body weight.

Statistical Analyses. Normality of all data was determined using a Shapiro-Wilk test and assessing the skewness and kurtosis of the data distribution. Participant demographics were compared between groups using independent samples *t* tests. Isokinetic quadriceps peak torque, quadriceps peak torque LSI, hop distance, hop distance LSI, and biomechanical outcomes were compared between limbs and between groups using paired and independent samples *t* tests. Cohen *d* effect sizes with 95% confidence intervals were calculated to determine the magnitude of differences in the presence of statistical differences between limbs and between groups. Effect sizes were classified as weak ($<$0.19), small (0.2–0.49), moderate (0.5–0.79), or large ($>$0.8). Between-limb and group comparisons of biomechanical outcomes were performed using the Statistical Package for Social Sciences (v. 28; IBM). To determine the associations between isokinetic quadriceps strength symmetry and biomechanical outcomes of the ACLR involved limb, Pearson's *r* correlation coefficients were performed. Correlation coefficients were classified as negligible (0.0–0.29), low (0.3–0.49), moderate (0.5–0.65), high (0.7–0.89), or very high (0.9–1.0).[23] The α level was set a priori at $P \leq .05$ for all analyses.

RESULTS

Participants' demographics, strength, and hop data can be found in Table 1. The control group was 2.08 years older than the ACLR group ($t_{32} = -2.608$, $P = .014$, $d = -0.89$ [−1.60, −0.19]). Otherwise, groups were demographically alike. Isokinetic quadriceps peak torque was significantly lower in the involved limb of the ACLR group than in the uninvolved limb ($t_{14} = -3.950$, $P = .001$, $d = -1.00$ [−1.72, −0.29]) and matched involved limb ($t_{31} = -3.718$, $P < .001$, $d = -1.31$ [−2.05, −0.56]) of the control group. Quadriceps peak torque symmetry indices were also significantly lower in the ACLR group than in the control group ($t_{31} = -3.958$, $P < 0.001$, $d = -1.38$ [−2.13, −0.63]). Hop distance and hop distance symmetry were not statistically different between limbs or between groups.

Loading Phase

Means and standard deviations of peak kinematics and kinetics during the loading phase are reported in Tables 2 and 3, respectively. During the loading phase, those with ACLR demonstrated lesser peak knee flexion angles ($t_{15} = 2.393$, $P = .03$, $d = -0.60$ [0.06, 1.12]), knee extension moments ($t_{15} = -4.004$, $P = .001$, $d = -1.00$ [−1.60, −0.39]), and knee power absorption ($t_{15} = -3.327$, $P = .007$, $d = 0.79$ [0.21, 1.34]) in the involved limb than in the uninvolved limb. Additionally, the ACLR involved limb demonstrated lesser peak knee extension moments than the matched involved limb of the control group ($t_{32} = -2.980$, $P = .005$, $d = -1.02$ [−1.74, −0.30]).

Propulsion Phase

Means and standard deviations of peak kinematics and kinetics during the propulsion phase are reported in Tables 4 and 5, respectively. During the propulsion phase, those with ACLR demonstrated greater knee abduction excursion in involved limb than in the uninvolved limb ($t_{15} = 2.700$, $P = .016$, $d = 0.82$ [0.12, 1.52]). Additionally, the involved limb demonstrated lesser knee extension moments ($t_{15} = -2.448$, $P = .027$, $d = -0.61$ [−1.14, −0.07]), knee power generation ($t_{15} = -2.953$, $P = .01$, $d = -0.74$ [−1.28, −0.17]), and anterior-posterior GRFs ($t_{15} = -2.159$, $P = .047$, $d = -0.54$ [−1.06, −0.01]) than the uninvolved limb. The involved limb also demonstrated lesser knee ($t_{15} = -2.365$, $P = .032$, $d = -0.46$ [−1.17, 0.24]) and ankle ($t_{15} = -2.356$, $P = .032$, $d = -0.57$ [−1.27, 0.14])

Table 1. Participant Demographics and Functional Performance Comparisons

	ACLR ($n = 16$)	Control ($n = 18$)	P Value
Age (y)	20.25 ± 2.15[a]	22.33 ± 2.47	.014
Sex (men/women)	7/9	10/8	.492
Body mass (kg)	74.46 ± 14.01	70.35 ± 12.67	.376
Height (m)	1.77 ± 0.11	1.74 ± 0.09	.429
Time from surgery (mo)	39.5 ± 33.1	NA	—
Graft type (PT/HT/allograft)	9/6/1	NA	—
Isokinetic peak quadriceps torque (Nm/kg)			
Involved	2.09 ± 0.45[a]	2.82 ± 0.64	.001
Uninvolved	2.53 ± 0.43	2.74 ± 0.69	.150
Isokinetic quadriceps torque LSI (%)	83.19 ± 16.33[a]	104.28 ± 14.28	<.001
Normalized hop distance[b]			
Involved	0.73 ± 0.12	0.72 ± 0.14	.897
Uninvolved	0.80 ± 0.16	0.74 ± 0.12	.129
Hop distance LSI (%)	92.47 ± 12.61	99.82 ± 13.37	.111

Abbreviations: ACLR, anterior cruciate ligament reconstruction; HT, hamstring tendon graft; LSI, limb symmetry index; NA, not applicable; PT, patellar tendon graft.
[a] Significantly different from the control group ($P \leq .05$).
[b] Normalized hop distance is expressed as a unitless ratio.

work generation than the uninvolved limb. Between-group comparisons revealed that the ACLR uninvolved limb demonstrated lesser hip abduction moments than the matched uninvolved limb of the control group ($t_{32} = 2.120$, $P = .042$, $d = 0.73$ [0.03, 1.42]).

Quadriceps Strength Symmetry Correlations

For individuals with ACLR, lesser quadriceps isokinetic strength symmetry was associated with lesser peak knee abduction moments ($r = -0.605$, $P = .017$), lesser knee power absorption ($r = -0.654$, $P = .008$), and greater trunk lean toward the stance limb ($r = -0.546$, $P = .035$) in the involved limb during the loading phase. Additionally, lesser quadriceps isokinetic strength symmetry was associated with greater peak hip flexion angles ($r = -0.602$, $P = .018$), greater peak knee flexion angles ($r = 0.688$, $P = .005$), and lesser peak ankle plantar flexion angles ($r = -0.543$, $P = .036$) in the involved limb during the propulsion phase. Lesser quadriceps strength symmetry was also associated with lesser joint excursions in the sagittal plane at the hip ($r = 0.582$, $P = .023$), knee ($r = 0.828$, $P < .001$), and ankle ($r = 0.661$, $P = .007$) in the involved limb during the propulsion phase.

DISCUSSION

The purpose of this study was to compare how individuals with ACLR perform the take-off of the SLHD in each limb and compare their performance with uninjured control individuals by breaking down the loading and propulsion phases of this task. Our secondary aim was to determine the relationships between quadriceps strength symmetry and take-off biomechanics during each phase. Individuals with ACLR achieved similar hop distances in both the involved and uninvolved limb compared with controls, despite presenting with large-magnitude quadriceps strength asymmetries and using knee-avoidance strategies. Our hypotheses were partially supported in that greater quadriceps strength asymmetry was associated with lower extremity biomechanics that reflect less loading of the knee and overall lesser range of motion of the hip, knee, and ankle in the involved limb explored during the propulsion phase. Collectively, these results advance our understanding of take-off strategies during the SLHD in individuals with ACLR.

Individuals with ACLR commonly achieve satisfactory hop performance, despite quadriceps strength deficits being present at discharge from rehabilitation.[7,24] These findings

Table 2. Peak Joint Angles (°) During the Loading Phase of the SLHD

	ACLR		Control	
Variables	Involved	Uninvolved	Matched Involved	Matched Uninvolved
Trunk				
Flexion	−54.62 ± 10.86	−54.52 ± 12.66	−51.78 ± 10.73	−49.20 ± 12.69
Lateral flexion	10.98 ± 3.75	11.72 ± 5.92	10.97 ± 5.13	8.81 ± 6.84
Hip				
Flexion	64.32 ± 11.76	64.55 ± 14.31	65.07 ± 12.03	63.02 ± 9.76
Adduction	9.26 ± 4.55	6.91 ± 6.55	10.44 ± 7.59	8.19 ± 6.32
Knee				
Flexion	−56.42 ± 5.35[a]	−59.58 ± 5.62	−59.90 ± 9.00	−58.37 ± 8.07
Abduction	−6.44 ± 5.07	−9.21 ± 5.12	−6.04 ± 5.36	−7.06 ± 4.98
Ankle				
Dorsiflexion	32.54 ± 3.12	34.35 ± 4.10	32.26 ± 5.85	33.60 ± 4.93
Eversion	−12.23 ± 7.80	−13.45 ± 8.72	−10.37 ± 26.00	−12.84 ± 16.16

Abbreviations: ACLR, anterior cruciate ligament reconstruction; SLHD, single-leg hop for distance.
[a] Significantly different from uninvolved ($P \leq .05$).

Table 3. Peak Kinetic Variables During the Loading Phase

Variables[a]	ACLR		Control	
	Involved	Uninvolved	Control Involved	Control Uninvolved
Hip				
Extension moment	−1.69 ± 0.34	−1.63 ± 0.30	−1.59 ± 0.36	−1.56 ± 0.31
Adduction moment	−0.71 ± 0.22	−0.63 ± 0.18	−0.65 ± 0.21	−0.76 ± 0.25
Power absorption	−2.32 ± 0.89	−2.07 ± 0.78	−1.90 ± 1.04	−1.79 ± 0.96
Work absorption	−0.46 ± 0.23	−0.39 ± 0.17	−0.43 ± 0.24	−0.45 ± 0.26
Knee				
Extension moment	0.47 ± 0.19[b,c]	0.67 ± 0.22	0.70 ± 0.25	0.67 ± 0.24
Adduction moment	−0.24 ± 0.22	−0.21 ± 0.12	−0.19 ± 0.16	−0.22 ± 0.96
Power absorption	−0.82 ± 0.45[b]	−1.15 ± 0.52	−1.19 ± 0.73	−1.24 ± 0.61
Work absorption	−0.12 ± 0.18	−0.17 ± 0.18	−0.25 ± 0.24	−0.24 ± 0.25
Ankle				
Plantarflexion moment	−1.44 ± 0.19	−1.50 ± 0.21	−1.30 ± 0.42	−1.37 ± 0.31
Inversion moment	6.16 ± 6.53	5.11 ± 4.37	5.01 ± 2.05	5.30 ± 4.58
Power absorption	−2.23 ± 0.75	−2.65 ± 1.14	−2.08 ± 0.95	−1.98 ± 0.91
Work absorption	−0.40 ± 0.09	−0.43 ± 0.10	−0.37 ± 0.13	−0.39 ± 0.13
GRF				
Vertical	1.69 ± 0.14	1.75 ± 0.18	1.67 ± 0.23	1.71 ± 0.27
A-P	0.44 ± 0.07	0.44 ± 0.10	0.40 ± 0.10	0.41 ± 0.09

Abbreviations: ACLR, anterior cruciate ligament reconstruction; A-P, anterior-posterior; GRF, ground reaction force.
[a] Moments are all normalized to the product of body mass × height (Nm/kg × m), ground reaction forces are all normalized to body weight, joint power (W/kg) and work (J/kg) are all normalized to body mass, and joint power and work were only calculated in the sagittal plane.
[b] Significantly different from uninvolved ($P \leq .05$).
[c] Significantly different from control involved ($P \leq .05$).

suggest that patients use alternative strategies to achieve similar height-normalized hop distances as their uninvolved limb and as uninjured individuals. Of the few studies that investigate the take-off phase of the SLHD, the loading phase has not been assessed during take-off.[10,19] This is a critical phase of the SLHD as it describes lower limb energy absorption in preparation for propulsion and distribution of loads across the lower extremity.

Individuals with ACLR loaded the involved limb with lesser peak knee flexion angles, knee extension moments, and knee power absorption than the uninvolved limb and lesser knee extension moments than matched controls. These data suggest that the quadriceps of the involved limb may not be able to produce or accept loads at a similar capacity as the uninvolved limb or uninjured controls due to persistent strength deficits. In turn, patients demonstrating

Table 4. Peak Joint Angles (°) During the Propulsion Phase

Variables	ACLR		Control	
	Involved	Uninvolved	Control Involved	Control Uninvolved
Trunk				
Extension	−16.76 ± 4.37	−16.00 ± 4.59	−14.05 ± 7.83	−13.44 ± 6.22
Sagittal excursion	28.29 ± 7.86	27.78 ± 6.74	29.81 ± 11.31	26.46 ± 8.80
Lateral flexion	11.36 ± 3.97	11.38 ± 5.92	11.25 ± 4.86	9.48 ± 7.27
Frontal excursion	1.21 ± 1.48	1.02 ± 1.34	1.51 ± 2.24	2.22 ± 2.99
Hip				
Extension	9.46 ± 12.43	8.48 ± 10.07	10.17 ± 10.19	10.38 ± 10.96
Sagittal excursion	45.42 ± 9.53	44.93 ± 7.50	46.72 ± 17.61	42.44 ± 13.05
Abduction	−7.25 ± 3.97	−8.90 ± 6.83	−5.39 ± 8.59	−10.13 ± 10.86
Frontal excursion	13.29 ± 5.02	11.62 ± 4.32	13.18 ± 6.89	14.47 ± 6.90
Knee				
Extension	−25.70 ± 7.53	−24.86 ± 5.67	−25.21 ± 8.23	−24.63 ± 10.25
Sagittal excursion	30.72 ± 9.33	34.70 ± 6.35	34.73 ± 13.32	32.92 ± 12.52
Abduction	−7.41 ± 4.74	−9.49 ± 5.43	−7.27 ± 5.73	−7.98 ± 5.73
Frontal excursion	2.34 ± 2.09[a]	1.07 ± 1.04	2.18 ± 1.98	2.00 ± 2.52
Ankle				
Plantar flexion	−14.73 ± 6.64	−15.56 ± 6.34	−14.05 ± 7.47	−14.51 ± 10.05
Sagittal excursion	47.06 ± 6.65	49.49 ± 5.61	45.40 ± 10.60	46.50 ± 9.62
Eversion	−0.81 ± 8.14	−0.31 ± 10.51	−3.86 ± 10.13	−2.14 ± 15.47
Frontal excursion	8.67 ± 3.56	10.19 ± 4.45	10.89 ± 11.52	7.75 ± 3.67

Abbreviation: ACLR, anterior cruciate ligament reconstruction.
[a] Significantly different from uninvolved ($P \leq .05$).

Table 5. Peak Kinetic Variables During the Propulsion Phase

Variables[a]	ACLR		Control	
	Involved	Uninvolved	Control Involved	Control Uninvolved
Hip				
Flexion moment	0.75 ± 0.13	0.72 ± 0.13	0.77 ± 0.13	0.75 ± 0.13
Abduction moment	−0.78 ± 0.21	−0.67 ± 0.17[c]	−0.72 ± 0.23	0.81 ± 0.20
Power generation	7.52 ± 1.65	7.31 ± 1.38	7.15 ± 2.42	6.96 ± 2.37
Work generation	1.40 ± 0.46	1.38 ± 0.39	1.33 ± 0.51	1.31 ± 0.45
Knee				
Extension moment	0.65 ± 0.26[b]	0.80 ± 0.25	0.82 ± 0.26	0.75 ± 0.24
Adduction moment	−0.23 ± 0.18	−0.19 ± 0.16	−0.20 ± 0.22	−0.19 ± 0.15
Power generation	3.88 ± 2.22[b]	5.08 ± 2.11	4.87 ± 2.13	4.21 ± 1.94
Work generation	0.26 ± 0.21[b]	0.36 ± 0.22	0.39 ± 0.18	0.30 ± 0.17
Ankle				
Plantarflexion moment	−1.70 ± 0.10	−1.76 ± 0.20	−1.69 ± 0.20	−1.72 ± 0.19
Inversion moment	−16.48 ± 13.92	−15.08 ± 13.48	−13.25 ± 9.58	−15.60 ± 12.88
Power generation	14.56 ± 2.38	15.73 ± 2.73	14.89 ± 2.64	14.90 ± 2.92
Work generation	1.19 ± 0.25[b]	1.34 ± 0.28	1.25 ± 0.27	1.27 ± 0.26
GRF				
Vertical	1.90 ± 0.12	1.95 ± 0.16	1.92 ± 0.21	1.93 ± 0.19
A-P	0.54 ± 0.09[b]	0.56 ± 0.09	0.54 ± 0.06	0.54 ± 0.07

Abbreviations: ACLR, anterior cruciate ligament reconstruction; A-P, anterior-posterior; GRF, ground reaction forces.

[a] Moments are all normalized to the product of body mass × height (Nm/kg × m), ground reaction forces are normalized by body weight, joint power (W/kg) and work (J/kg) are all normalized to body mass, and joint power and work were only calculated in the sagittal plane.

[b] Significantly different from uninvolved ($P \leq .05$).

[c] Significant different from control uninvolved ($P \leq .05$).

smaller knee flexion excursions or using a knee-avoidance strategy, may also limit loading of the quadriceps and contribute to poor muscle adaptations. Individuals with a larger magnitude of quadriceps strength asymmetry and generalized quadriceps weakness after ACLR are reported to land from the SLHD with lesser knee flexion angles and knee extensor moments.[8,11,19] Although evaluated at a different phase of the SLHD, the differences in joint loading mechanics in our study further support that the quadriceps are unable to generate and attenuate forces throughout take-off due to persistent weakness. Our findings highlight the importance of addressing quadriceps strength deficits and knee-avoidance strategies during rehabilitation. Training the quadriceps to be loaded appropriately during single-leg tasks would better prepare patients to appropriately load the joint in sport scenarios where they cannot use the contralateral limb to attenuate forces applied.

Participants with lower quadriceps strength symmetry also demonstrated lesser knee adduction moments, lesser knee power absorption, and greater ipsilateral trunk flexion during the loading phase in the involved limb. Previous literature has reported greater forward and ipsilateral trunk flexion angles in individuals with ACLR during landing phases of the SLHD.[19,25] Increased forward and ipsilateral trunk flexion angles shift the center of mass, reducing quadriceps demand. Persistent off-loading of the knee could contribute to future dysfunction of the quadriceps through quadriceps avoidance and underloading.[26] Underloading of the knee has been observed during gait, sit-to-stand tasks, squatting, running, cutting, and bilateral and unilateral landings following ACLR.[12,14–16,27–29] Our findings and previous literature collectively highlight the underloading across a variety of tasks and may have implications for potential secondary injury and long-term joint health through repetitive underloading due to the inability of the quadriceps to attenuate loads during functional activities. Therefore, the loading phase of the SLHD needs to be considered when patients are performing this task, as this can provide insight as to whether or not they are able to appropriately load the involved limb across multiple functional tasks and not just sport.

We observed lesser peak knee extension moments, peak knee power generation, and knee and ankle work generation than in the uninvolved limb during the propulsion phase of the SLHD.[10,19] Our results are in agreement with previous literature, which would collectively support that the contributions of the knee during the propulsion phase of take-off are limited.[19] Previous literature has reported conflicting evidence of the contributions of other joints to the propulsion of the SLHD.[10,19,30,31] Similar to Kotsifaki et al, our sample demonstrated significantly less knee and ankle work generation during propulsion in the involved limb, which is further supported by other reports of greater hip flexion and lesser ankle range of motion, suggesting a hip-dominant strategy.[10,19,31] However, there are conflicting reports where some individuals with ACLR presented with less hip flexion in the involved limb throughout the majority of the propulsion phase.[30] The conflicting reports of compensatory strategies at the hip to off-load the knee may indicate that these changes following ACLR are individualized and may be masked by group comparisons. Future research should consider subgroup comparisons of hop performance based on quadriceps strength to further understand factors influencing knee-avoidance strategies.

We also found that when the involved limb was performing the hop, there were lesser horizontal GRFs than the uninvolved limb, but no differences in vGRFs were observed. It is possible that center of mass displacement may be performed differently between limbs to achieve comparable hop distances. In healthy athletes performing a long jumping task, horizontal and vertical center of mass velocities should be similar at take-off to maximize displacement of the center of mass.[32] However, following ACLR, it is possible that these patients may be performing the hop with greater vertical displacements and velocities to compensate for the lack of posterior displacement of the center of mass, allowing them to still achieve hop distance symmetry. Potential changes in trajectories of the center of mass may explain how the involved limb demonstrates similar hop distances despite lower propulsion. Future research should consider calculating the center of mass displacement, velocity, and angle of trajectory during propulsion of the SLHD to further investigate compensatory strategies to perform this task.

Although the propulsion phase has been investigated in recent years, the contribution of quadriceps strength herein adds new context. Those with greater quadriceps strength asymmetry presented with lesser hip, knee, and ankle range of motion in the involved limb during the propulsion phase of the SLHD. Previous literature have also reported lesser range of motion explored in the hip, knee, and ankle during the propulsion phase of the SLHD.[10,31] Greater quadriceps strength asymmetry is also associated with less hip and knee extension and less ankle plantar flexion angles in the involved limb during the propulsion phase. Additionally, the individuals with greater quadriceps strength asymmetry could be driving the deficits of ankle work generation during the propulsion phase and may explain the relationship with lesser peak ankle plantar flexion. Individuals with greater isokinetic quadriceps strength asymmetry may be performing the propulsion with “stiffer” movement patterns, which may be restricting optimal performance of the task. These results would further support the need for a holistic approach to hop performance assessments rather than just accounting for hop distance as passing criteria.

Clinical Implications

Individuals with ACLR achieve satisfactory limb symmetry for hop distance earlier in rehabilitation than quadriceps strength, suggesting that clinical assessments of hop performance have the potential to mask quadriceps dysfunction from either limb.[5,7] Simultaneously passing strength and hop criteria should be a priority for clinicians treating patients with ACLR, as quadriceps strength asymmetry was associated with knee off-loading movement patterns in the present study. Given the nature of differences reported during the take-off and landing phases of the SLHD, criteria relating to the quality of movement during the loading and propulsion phases of the SLHD could be defined to better inform return to unrestricted physical activity decisions.[33] Unfortunately, instrumented approaches are unlikely to be feasible in clinical settings, presenting a critical barrier to screening in clinical practice. Future research should establish movement quality criteria for the take-off of the SLHD using tools that are readily available to clinicians (eg, 2-dimensional video analysis), especially with hopping tasks being commonly used for return-to-sport criteria, an approach that has been successful in the assessment of the landing phase of the SLHD and drop jump landing techniques.[34–36] Measuring hop distances alone for return-to-sport criteria overestimates the function of the patient and may falsely recommend progression into more functional tasks before they are physically ready. Although LSI scores exceeded 90% for hop distance in our sample, we were able to detect clinically relevant differences in loading patterns between limbs. Therefore, we caution the sole reliance of hop symmetry to determine readiness to return to sport, and finding targeted interventions is necessary to restore normative loading in the injured knee. Using neuromuscular training with external biofeedback based on the patient’s loading patterns could help restore loading symmetry between limbs and prevent the knee-avoidance strategy observed in this study.[37]

Limitations

With our sample, we had a heterogenous group of individuals with ACLR. Our participants experienced different surgical techniques from a variety of surgeons and completed rehabilitation with different clinicians in the area. It is possible that surgical technique, rehabilitation protocols, and graft type could have influenced how our participants were performing the take-off of the SLHD. Our study did not impose a time-from-surgery cutoff for patients with ACLR, who were, on average, slightly more than 3 years postsurgery. Future research should consider controlling these variables to minimize the influence of these factors on performance of the take-off of the SLHD. We also did not evaluate the influence of sex on our outcome measures. Females with ACLR have reported greater strength deficits and strength asymmetry than their male counterparts, suggesting a difference in response to rehabilitation from the surgery.[38,39] It is possible that the female participants with ACLR could be driving the relationships between quadriceps strength asymmetry and take-off biomechanics. Future research should determine the differences of these take-off phases between sexes to help further understand how nonmodifiable factors could influence the performance of the SLHD.

The involved limb of individuals with ACLR demonstrated movement patterns indicative of an off-loading strategy at the knee during the loading and propulsion phases of the SLHD. Additionally, quadriceps strength asymmetry was moderately to strongly correlated with the stiffer movement patterns observed during the take-off phases, suggesting a need to address these deficits during rehabilitation before patients return to unrestricted physical activity. Our results further support that traditional clinical hop distance criteria do not inform clinicians of the quality of the SLHD. Our sample was able to achieve greater than 90% symmetry regardless of demonstrating greater quadriceps strength asymmetry, suggesting a continued need to investigate compensatory strategies at the trunk, hip, and ankle during the loading phase.

REFERENCES

1. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27(12):1697–1705. doi:10.1016/j.arthro.2011.09.009
2. Burgi CR, Peters S, Ardern CL, et al. Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *Br J Sports Med*. 2019;53(18):1154–1161. doi:10.1136/bjsports-2018-099982
3. Hegedus EJ, McDonough S, Bleakley C, Cook CE, Baxter GD. Clinician-friendly lower extremity physical performance measures in

athletes: a systematic review of measurement properties and correlation with injury, part 1. The tests for knee function including the hop tests. *Br J Sports Med*. 2015;49(10):642–648. doi:10.1136/bjsports-2014-094094
4. Toole AR, Ithurburn MP, Rauh MJ, Hewett TE, Paterno MV, Schmitt LC. Young athletes cleared for sports participation after anterior cruciate ligament reconstruction: how many actually meet recommended return-to-sport criterion cutoffs? *J Orthop Sports Phys Ther*. 2017;47(11):825–833. doi:10.2519/jospt.2017.7227
5. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *J Orthop Sports Phys Ther*. 2017;47(5):334–338. doi:10.2519/jospt.2017.7285
6. Chaput M, Palimenio M, Farmer B, et al. Quadriceps strength influences patient function more than single leg forward hop during late-stage ACL rehabilitation. *Int J Sports Phys Ther*. 2021;16(1):145–155. doi:10.26603/001c.18709
7. Nagai T, Schilaty ND, Laskowski ER, Hewett TE. Hop tests can result in higher limb symmetry index values than isokinetic strength and leg press tests in patients following ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(3):816–822. doi:10.1007/s00167-019-05513-3
8. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *Am J Sports Med*. 2015;43(7):1662–1669. doi:10.1177/0363546515578252
9. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports*. 2010;20(1):e12–e19. doi:10.1111/j.1600-0838.2008.00873.x
10. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(11):1587–1593. doi:10.1007/s00167-010-1185-2
11. Xergia SA, Pappas E, Zampeli F, Georgiou S, Georgoulis AD. Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2013;43(3):154–162. doi:10.2519/jospt.2013.3967
12. Chan MS, Sigward SM. Loading behaviors do not match loading abilities postanterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2019;51(8):1626–1634. doi:10.1249/MSS.0000000000001956
13. Chan MS, Sigward SM. Individuals following anterior cruciate ligament reconstruction practice underloading strategies during daily activity. *J Orthop Res*. 2022;40(3):565–572. doi:10.1002/jor.25070
14. de Fontenay BP, Roy JS, Plemmons M, Willy R. Knee joint underloading does not evolve after a two-week reintroduction to running program after anterior cruciate ligament reconstruction. *Phys Ther Sport*. 2023;61:122–128. doi:10.1016/j.ptsp.2023.03.003
15. Lepley AS, Kuenze CM. Hip and knee kinematics and kinetics during landing tasks after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *J Athl Train*. 2018;53(2):144–159. doi:10.4085/1062-6050-334-16
16. Shimizu T, Samaan MA, Tanaka MS, et al. Abnormal biomechanics at 6 months are associated with cartilage degeneration at 3 years after anterior cruciate ligament reconstruction. *Arthroscopy*. 2019;35(2):511–520. doi:10.1016/j.arthro.2018.07.033
17. Moore C, Donovan L, Murray AM, Armstrong C, Glaviano NR. External ankle taping does not alter lower extremity side-step cut and straight sprint biomechanics in young adult males. *Sports Biomech*. 2020;19(3):395–410. doi:10.1080/14763141.2018.1493743
18. Tawy GF, Rowe P. Is the instrumented-pointer method of calibrating anatomical landmarks in 3D motion analysis reliable? *J Biomech*. 2017;53:205–209. doi:10.1016/j.jbiomech.2017.01.019
19. Kotsifaki A, Whiteley R, Van Rossom S, et al. Single leg hop for distance symmetry masks lower limb biomechanics: time to discuss hop distance as decision criterion for return to sport after ACL reconstruction? *Br J Sports Med*. 2022;56(5):249–256. doi:10.1136/bjsports-2020-103677
20. Chen AJ, Tatarski RL, Perry J, Quatman CE, Hewett TE, Di Stasi S. Single-leg hop mechanics are correlated with self-reported knee function early after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon)*. 2020;73:35–45. doi:10.1016/j.clinbiomech.2019.12.020
21. Bley AS, Correa JC, Dos Reis AC, Rabelo ND, Marchetti PH, Lucareli PR. Propulsion phase of the single leg triple hop test in women with patellofemoral pain syndrome: a biomechanical study. *PLoS One*. 2014;9(5):e97606. doi:10.1371/journal.pone.0097606
22. Mulligan CMS, Gibbs ER, Huang YL, Stutzenberger LR, Johnson ST, Norcross MF. Single-leg triple-hop propulsion strategies in females with and those without a history of anterior cruciate ligament reconstruction. *J Athl Train*. 2023;8(4):319–328. doi:10.4085/1062-6050-0676.21
23. Mukaka MM. Statistics corner: a guide to appropriate use of correlation coefficient in medical research. *Malawi Med J*. 2012;24(3):69–71.
24. Norte GE, Goetschius JW, Slater LV, Hart JM. Influence of patient demographics and surgical characteristics on pass rates of return-to-activity tests in anterior cruciate ligament-reconstructed patients before physician clearance. *Clin J Sport Med*. 2021;31(6):e354–e362. doi:10.1097/JSM.0000000000000790
25. Oberländer KD, Brüggemann GP, Höher J, Karamanidis K. Altered landing mechanics in ACL-reconstructed patients. *Med Sci Sports Exerc*. 2013;45(3):506–513. doi:10.1249/MSS.0b013e3182752ae3
26. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. *J Athl Train*. 2010;45(1):87–97. doi:10.4085/1062-6050-45.1.87
27. Pietrosimone B, Loeser RF, Blackburn JT, et al. Biochemical markers of cartilage metabolism are associated with walking biomechanics 6-months following anterior cruciate ligament reconstruction. *J Orthop Res*. 2017;35(10):2288–2297. doi:10.1002/jor.23534
28. Strong A, Markström JL, Schelin L, Häger CK. Asymmetric loading strategies during squats following anterior cruciate ligament reconstruction: a longitudinal investigation with curve analyses throughout and after rehabilitation. *Scand J Med Sci Sports*. 2024;34(1):e14524. doi:10.1111/sms.14524
29. Kaiyala M, Hannigan JJ, Traut A, Pollard C. Bilateral movement asymmetries exist in recreational athletes during a 45° sidestep cut post-anterior cruciate ligament reconstruction. *PeerJ*. 2024;12:e16948. doi:10.7717/peerj.16948
30. Huby CL, Miari I, Hagen M, Verschueren S, Vanrenterghem J, Smeets A. Push-off dynamics reveal task-independent alterations in athletes returning to sport after ACL reconstruction. *Med Sci Sports Exerc*. 2022;54(12):2045–2053. doi:10.1249/MSS.0000000000002994
31. Wren TAL, Mueske NM, Brophy CH, et al. Hop distance symmetry does not indicate normal landing biomechanics in adolescent athletes with recent anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2018;48(8):622–629. doi:10.2519/jospt.2018.7817
32. Hay JG, Miller JA, Canterna RW. The techniques of elite male long jumpers. *J Biomech*. 1986;19(10):855–866. doi:10.1016/0021-9290(86)90136-3
33. Kotsifaki A, Korakakis V, Whiteley R, Van Rossom S, Jonkers I. Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis. *Br J Sports Med*. 2020;54(3):139–153. doi:10.1136/bjsports-2018-099918
34. Welling W, Benjaminse A, Seil R, Lemmink K, Gokeler A. Altered movement during single leg hop test after ACL reconstruction: implications to incorporate 2-D video movement analysis for hop tests. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(10):3012–3019. doi:10.1007/s00167-018-4893-7

35. Bell DR, Smith MD, Pennuto AP, Stiffler MR, Olson ME. Jump-landing mechanics after anterior cruciate ligament reconstruction: a landing error scoring system study. *J Athl Train*. 2014;49(4):435–441. doi:10.4085/1062-6050-49.3.21
36. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE II, Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the JUMP-ACL study. *Am J Sports Med*. 2009;37(10):1996–2002. doi:10.1177/0363546509343200
37. Ericksen HM, Thomas AC, Gribble PA, Armstrong C, Rice M, Pietrosimone B. Jump-landing biomechanics following a 4-week real-time feedback intervention and retention. *Clin Biomech (Bristol, Avon)*. 2016;32:85–91. doi:10.1016/j.clinbiomech.2016.01.005
38. Maguire K, Sugimoto D, Micheli LJ, Kocher MS, Heyworth BE. Recovery after ACL reconstruction in male versus female adolescents: a matched, sex-based cohort analysis of 543 patients. *Orthop J Sports Med*. 2021;9(11):23259671211054804. doi:10.1177/23259671211054804
39. Kim DK, Park WH. Sex differences in knee strength deficit 1 year after anterior cruciate ligament reconstruction. *J Phys Ther Sci*. 2015;27(12):3847–3849. doi:10.1589/jpts.27.3847

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